Onset and nonlinear relaxation of coherent current-carrying edge filaments during transient events in tokamaks

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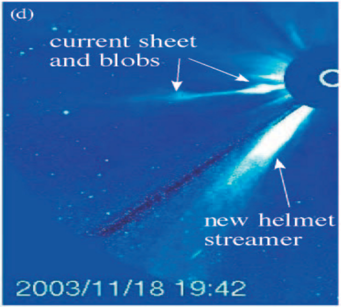
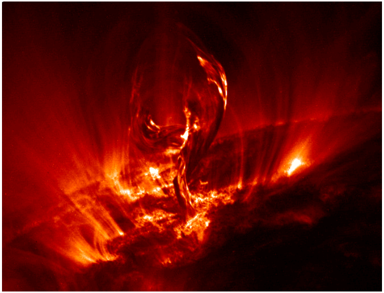
Magnetic reconnection energizes many processes in nature

There is numerous observational evidence of plasmoid-like structures in the solar atmosphere.

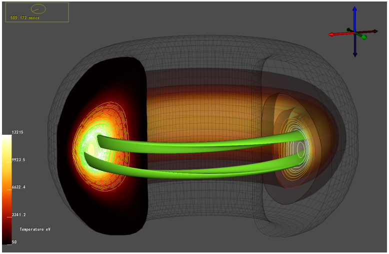


Plasmoids (2D) of the reconnected plasma flowing along the current sheet. LASCO/SOHO C3 images [Lin et al. 2005; Reily et al. 2007]



Current-carrying intertwining flux-tubes (3D) emerging from the surface of the sun. Helical kink instability of highly twisted flux rope [Karlicky& Kliem 2010]

Reconnection physics plays an important role in the nonlinear dynamics of many processes in laboratory plasmas



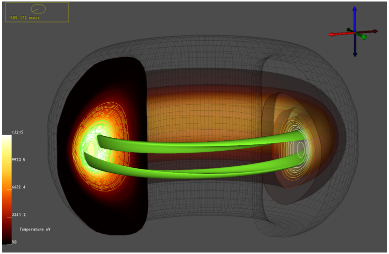
In toroidal fusion plasmas magnetic reconnection is mainly **spontaneous** as the result of tearing fluctuations (FKR ’63). **Classical tearing only makes a modest modification to the global current density.**

How about current sheets?

- Are there reconnecting coherent current-carrying structures in fusion plasmas?
- What are the implications of these structures for different nonlinear dynamics?
- Under what conditions could 2-D axisymmetric plasmoids or 3-D filaments be formed?

PPPL

Reconnection physics plays an important role in the nonlinear dynamics of many processes in laboratory plasmas



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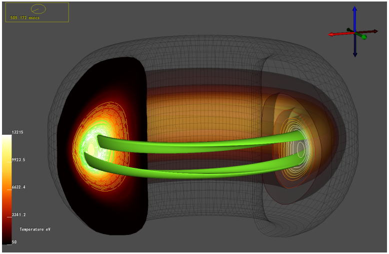

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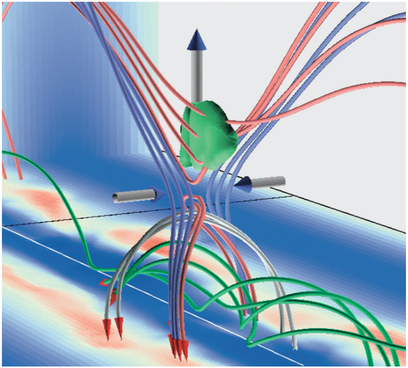
Many fundamentals of reconnection physics can be explored during helicity injection

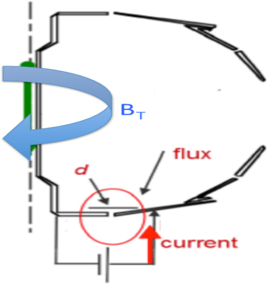
Solar flares field lines modeling



$$\frac{\partial K}{\partial t} = -2 \int (\mathbf{A}.\mathbf{V})\mathbf{B} \cdot d\mathbf{s}$$

Kusano 2004
Warnecke & Brandenburg 2010

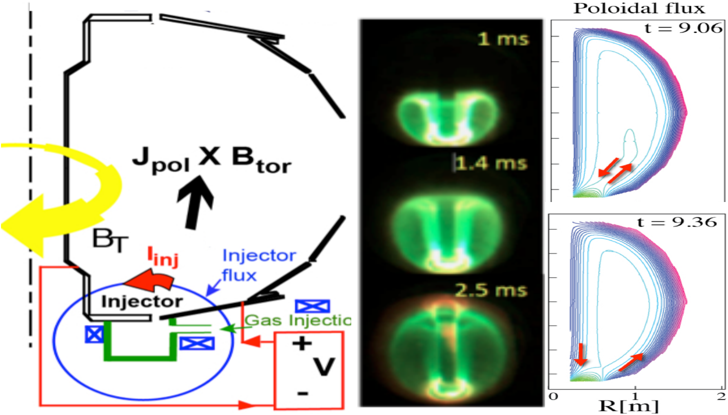
Helicity injection in a lab



$$\frac{\partial K}{\partial t} = -2 \int \Phi \mathbf{B} \cdot d\mathbf{s}$$

Helicity is injected through a surface term.

In transient CHI, axisymmetric reconnection generates a high quality closed flux start-up equilibrium in NSTX



Transient CHI is used as a solenoid-free plasma start-up method in NSTX & other Sts can be used to simplify the Tokamak.

Outline

Utilize the helicity injection technique to study:

- Flux surface closure during transient CHI
  - Forced (driven) S-P reconnection

    Ebrahimi et al. PoP 2013, 2014
  - Spontaneous plasmoid-mediated reconnection

    Ebrahimi & Raman PRL 2015,Ebrahimi & Raman NF 2016
- 3D effects
  - dynamo-driven reconnection plasmoids formation

    Ebrahimi PoP 2016
  - reconnecting Edge Localized Modes

    Ebrahimi PoP 2017

Nonlinear resistive MHD simulations using NIMROD code will be used to study reconnection physics.

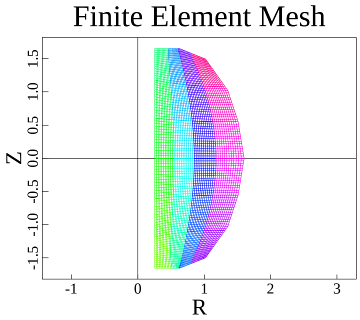
Helicity injection simulations are performed using the extended-MHD NIMROD code

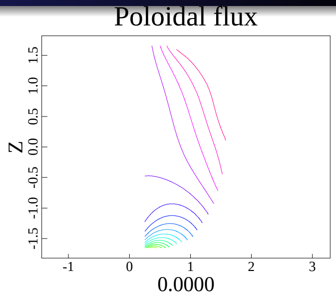
- Solves the linear and nonlinear MHD equations

$$\begin{aligned}
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla\times\mathbf{E} + \kappa_{divb}\nabla\nabla.\mathbf{B} \\
\mathbf{E} &= -\mathbf{V}\times\mathbf{B} + \eta\mathbf{J} + \frac{1}{ne}\mathbf{J}\times\mathbf{B} \\
\mathbf{J} &= \nabla\times\mathbf{B} \\
\frac{\partial n}{\partial t} + \nabla.(n\mathbf{V}) &= \nabla.D\nabla n \\
\rho(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V}.\nabla\mathbf{V}) &= \mathbf{J}\times\mathbf{B} - \nabla P - \nabla.\Pi \\
\frac{n}{(\Gamma-1)}(\frac{\partial T_\alpha}{\partial t} + \mathbf{V}.\nabla T_\alpha) &= -p_\alpha\nabla.\mathbf{V} - \nabla.\mathbf{q}_\alpha + Q
\end{aligned}$$

- $\mathbf{q} = -n[(\kappa_{||} - \kappa_\perp)\hat{b}\hat{b} + \kappa_\perp\mathbf{I}]\cdot\nabla T$
- Π is the stress tensor (also includes numerical $\rho\nu\nabla V$)
- κ_{divb} and D are magnetic-divergence and density diffusivities for numerical purposes.

The computational model (Nonlinear NIMROD simulations)

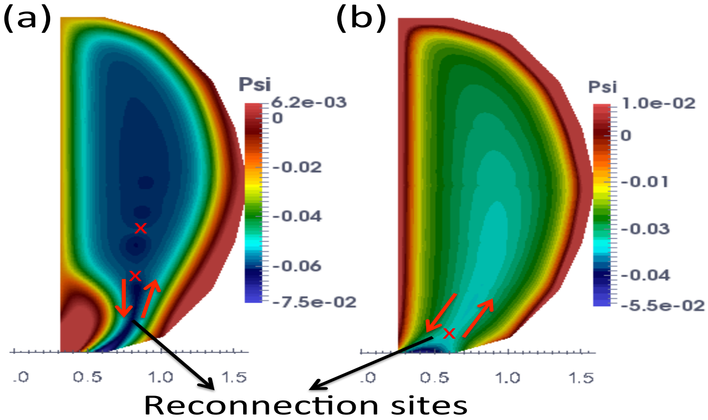




- Similar geometry to the experiment with a narrow slot.
- Initial Ψ_{inj} generated by including NSTX poloidal coil currents (with fixed boundary field)
  - Poloidal grid 45 $\times$ 90 fifth order finite elements, 2-D (n=0) and 3-D (up to n= 22 toroidal modes) simulations
  - Voltage is applied across the injector gap (V_{inj})
  - $E \times B$ normal flows at the gaps

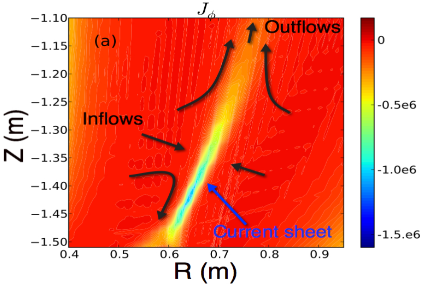
Reconnection could occur during both stages of helicity injection

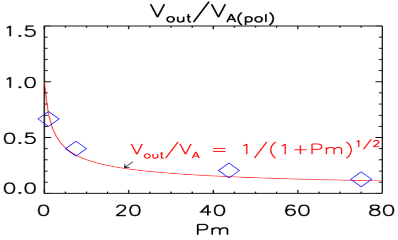
During injection (V_{inj} on) During decay (V_{inj} =0)



How are the closed flux surfaces formed?

I - Forced S-P reconnection





A local 2-D Sweet-Parker type reconnection is triggered in the injection region. Key signatures:

- **I - Elongated current sheets, $L > \delta$.**
- **II - Scaling of the current sheet width $\delta/L \sim (1 + P_m)^{1/4} S^{-1/2} \sim V_{in}/V_{out}$**
- **III -Pinch inflow and Alfvénic outflow**

S = LV_A/η (Alfven velocity based on the reconnecting B, L is the current sheet length) F. Ebrahimi, et al. PoP 2013, 2014

Outline

- How are the closed flux surfaces formed?
  - **Forced (driven) S-P reconnection**
  - $\Longrightarrow$ **Spontaneous reconnection**

    Could the elongated current sheet become unstable?

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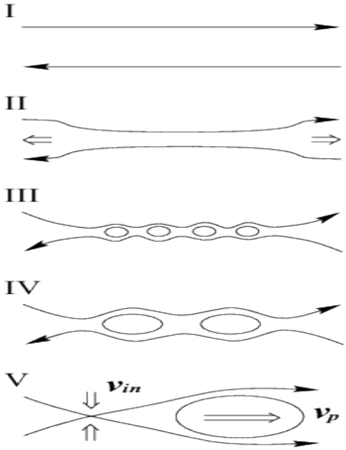
In many fast MHD dynamical processes, plasmoids are essential features (2-D)

Plasmoid instability: tearing instability in a current sheet

- Elongated current sheet can become tearing unstable at high S. [Biskamp 1986, Tajima & Shibata 1997]
- The scaling properties of a classical linear tearing changes, as the current-sheet width scales with S ($\gamma \sim S^{1/4}$).
- Numerical development: [Shibata & Tanuma 2001,Loureiro et al. 2007; Lapenta 2008; Daughton et al. 2009,; Bhattacharjee et al. 2009] **shows fast reconnection.**
- Static linear theory does not apply [L. Comisso et al. PoP 2016]



Shibata & Tanuma 2001

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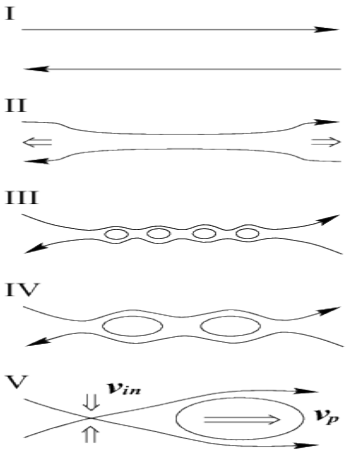
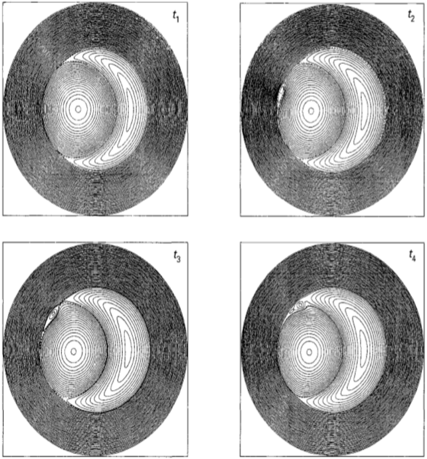


Shibata & Tanuma 2001

Secondary islands (plasmoids) in tokamak-relevant studies

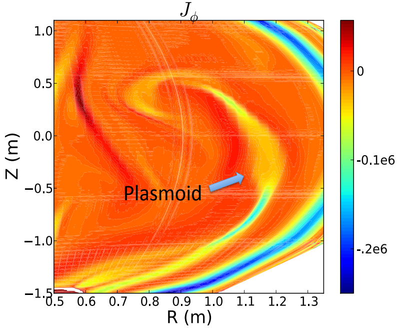
- Secondary islands (plasmoids) seen in reduced MHD simulations during the nonlinear evolution of the tearing instability (at large Δ') in slab geometry [Loureiro et al. 2005], and during the nonlinear growth of an internal kink mode in cylindrical geometry [Gunter et al. 2015]

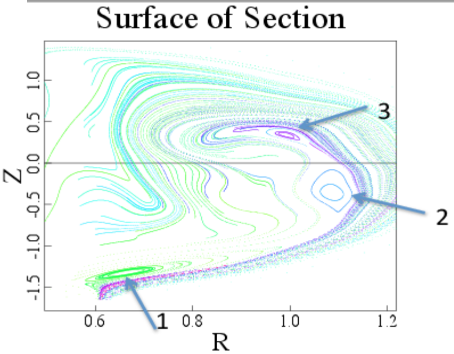
Plasmoid instability in the current sheet of the resistive kink mode



Biskamp 1987

Elongated current sheet becomes unstable - plasmoids form





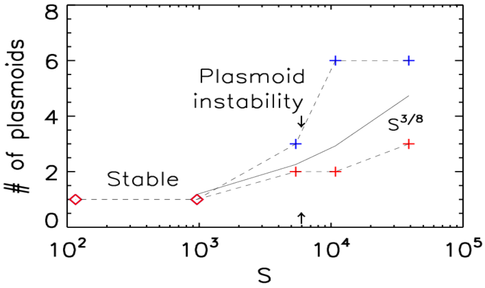
At high S, a transition to a plasmoid instability is demonstrated in the simulations

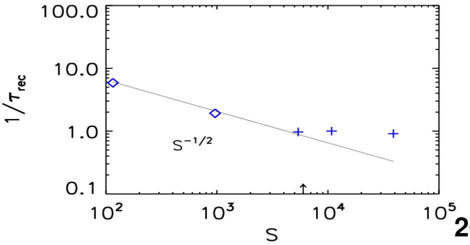
Both small sized transient plasmoids and large system-size plasmoids are formed and co-exist (S=39000)

Plasmoids merge to form closed flux surfaces. Reconnection rate becomes nearly independent of S.

F. Ebrahimi and R.Raman PRL 2015

At high S, a transition to a plasmoid instability occurs





- Number of plasmoids is an increasing function of S. Blue: small sized transient plasmoids Red: large scale and persistent plasmoids
- As the current sheet evolves in time, static linear theory doesn't apply [L. Comisso et al. PoP 2016]
- Reconnection rate becomes nearly independent of S. **[Here with strong guide field]**

F. Ebrahimi & R.Raman PRL 2015

First documentation of plasmoid formation in MHD regime in laboratory.

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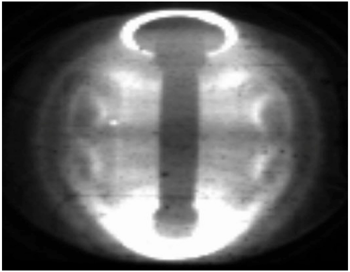

Camera images from NSTX do show the formation plasmoids that then merge into a larger plasma

[Ebrahimi&Raman PRL 2015]

Plasmoid instability with continued injection of plasmoids is observed during the injection phase (S $\sim$ 29000)

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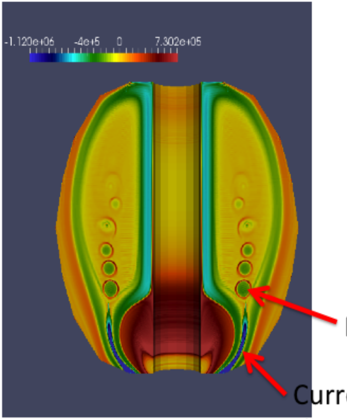
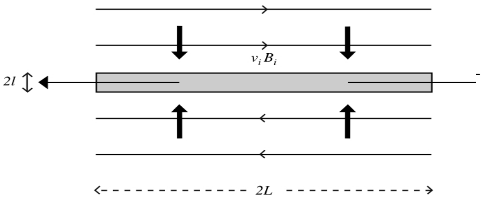


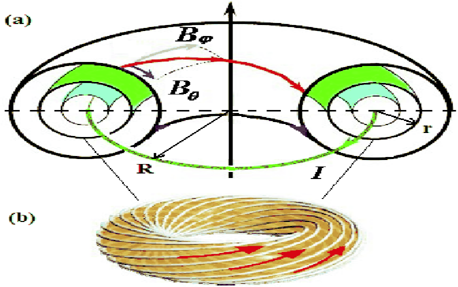
- 3-D effects
  - Could 3-D fluctuations (and large-scale dynamo from fluctuations) **trigger** 2-D global reconnection or 2-D reconnecting plasmoids?
  - **Self-consistent trigger mechanism in 3-D**
  - Flux closure during CHI plasma start-up in 3-D

2-D (n=0) modes



- A rare, classical example of 2-D plasmoid formation during CHI near the injection region (with the resonant surface $\mathbf{k} \cdot \mathbf{B} = 0$ at the null surface of the poloidal equilibrium field)

3-D ($n \neq 0$)

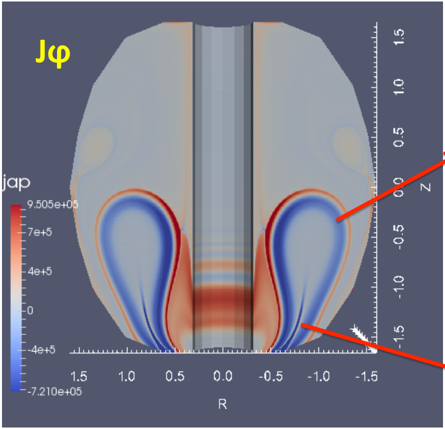


$\mathbf{B} = B_\theta \hat{\theta} + B_\phi \hat{\phi}$

- Resonant surfaces where
  $k \cdot B = mB_\theta / r - nB_\phi / R = 0$
  $q = rB_\phi / RB_\theta = m/n$
  Finite (high) q & **n** in the edge

Edge current sheets/layers are dynamical not static

Two types of current sheets are formed during flux expansion/evolution



- 1- **Edge current sheet** from the poloidal flux compression near the plasma edge, **leads to 3-D filament structures**
- 2- **Primary reconnecting current sheet** from the oppositely directed field lines in the injector region, **leads to 2-D plasmoids**

F. Ebrahimi PoP 2016

In 3-D, edge current sheets could cause several dynamical processes

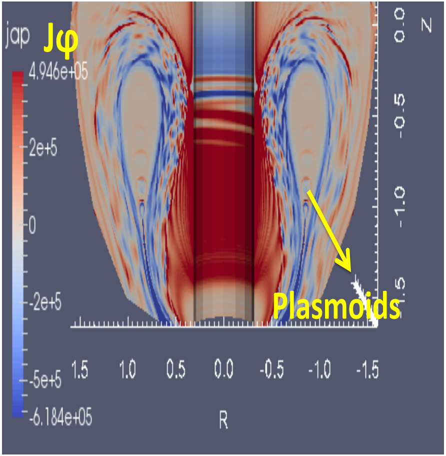
Edge current sheet/spikes can develop

- during flux expansion (during CHI)
- from pressure-driven edge bootstrap current
- due to strong current ramp up
- during vertical displacement of plasma [Ebrahimi PoP 2017]

Edge nonaxisymmetric current sheet instabilities grow on the poloidal Alfven time scales.

- **I - poloidal flux amplification to trigger axisymmetric**
- **II - low-n ELM peeling-driven filament structures**
- **III - reconnecting edge filaments during VDEs**

Edge current-sheet instabilities are triggered in 3-D, and break the current sheet



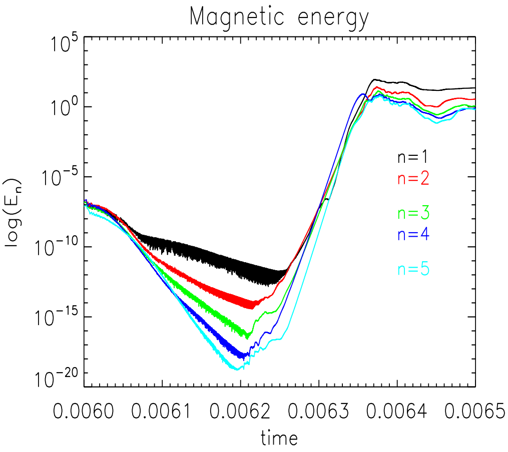
1. I- **Edge-localized modes arising from the asymmetric current-sheet instabilities**
2. II- With 3-D fluctuations, axisymmetric plasmoids are formed, **local S increased to S $\sim$ 15000.** [Ebrahimi PoP Letters 2016]

Edge modes grow on the poloidal Alfven time scales

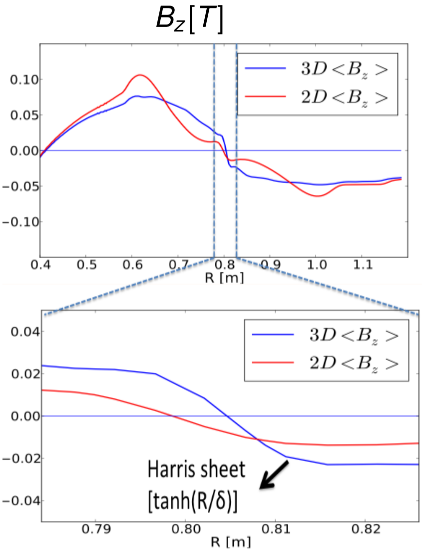
1. These modes grow fast, on the poloidal Alfven time scales, but they have tearing-parity structures.

2. These modes saturate by modifying and relaxing the edge current sheet

$\gamma\tau_{A(n=1)} = 0.16,$
$\gamma\tau_{A(n=2)} = 0.18,$
$\gamma\tau_{A(n=3)} = 0.2,$
$\gamma\tau_{A(n=4)} = 0.23,$
$\gamma\tau_{A(n=5)} = 0.26.$
$S = 2 \times 10^5$



I- A 3-D dynamo poloidal flux amplification is observed to trigger axisymmetric reconnecting plasmoids formation



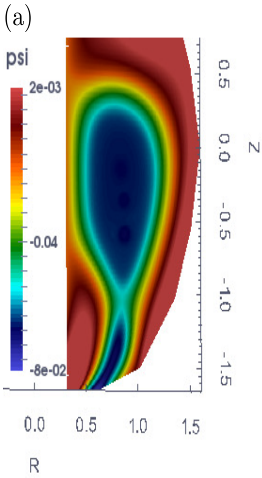
- For the first time a dynamo poloidal flux amplification is observed
- This **fluctuation-induced flux amplification increases the local S** ==> **triggers a plasmoid instability** ==> breaks the primary current sheet.

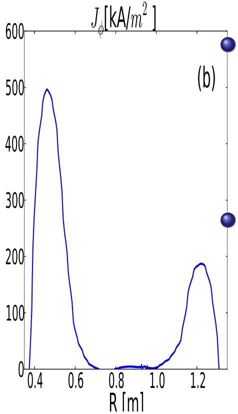
Model for current-driven ELMs

To capture the essential reconnection physics in the edge region of tokamak and to understand the quasiperiodic dynamics of low-n ELMs

- consider large edge current formed non-inductively (unlike pressure-driven current in the H-mode),
- isolate nonlinear evolution of edge current from the core
- simulations have local edge S = LV_A/η as high as 5×10^5, in the range of collisionality of standard tokamak operation

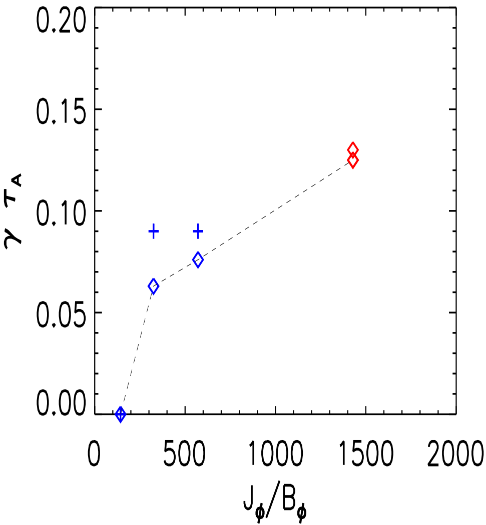
Edge current spikes provide the free energy for nonaxisymmetric edge instabilities





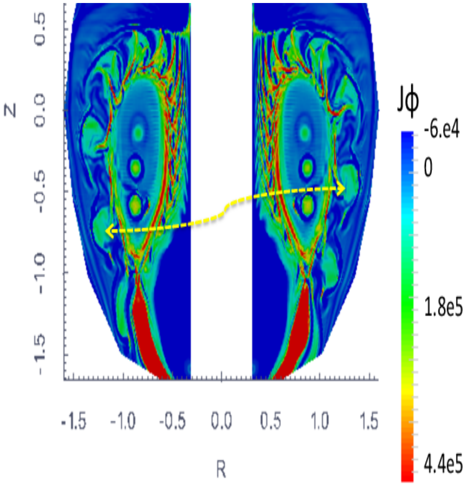
- Typical poloidal flux and axisymmetric toroidal current density during nonlinear simulations
- Unlike classical tearing, for current-sheet instability, edge current sheet width scales with S

The growth of current-driven reconnecting edge localized modes (with tearing parity) scales with $J_{||}/B$



- Simulations with varying B_ϕ = [2.8, 1.23, and 0.7T], but keeping the current-density profile fixed, $J_\phi = 400kA/m^2$ (S=11000) [blue diamonds]
- Scaling consistent with the instability drive for the traditional ideal peeling modes, $qRJ_{||}/B$
- Our limited scaling study for three S values in the range of $(1 - 4 \times 10^5)$ show a weak dependency on S.

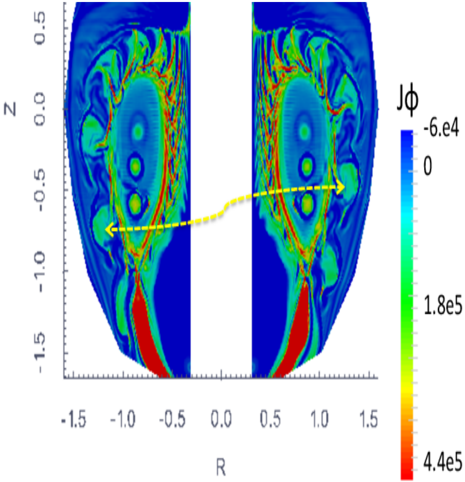
Nonlinear w/ 22 toroidal modes



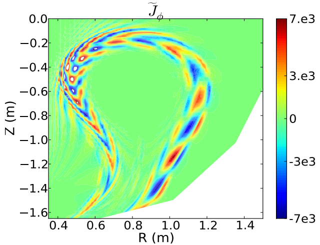
- Nonaxisymmetric structures break the initial axisymmetric current density
- Because of the very localized nature of the magnetic fluctuations, the amplitude of the associated perturbed toroidal current density can be as high as 50% of the n=0 component

The radially propagating filament n=1 structures can only become coherent as the number of toroidal modes increased

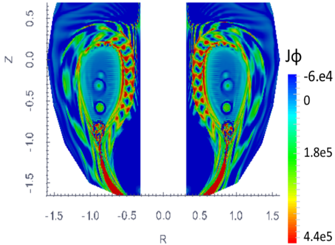
Nonlinear w/ 22 modes



Linear

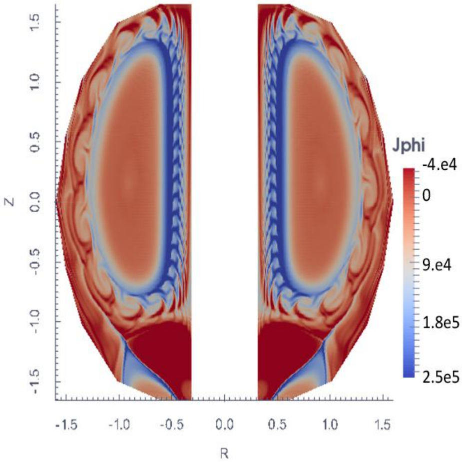


Nonlinear w/ 2 modes



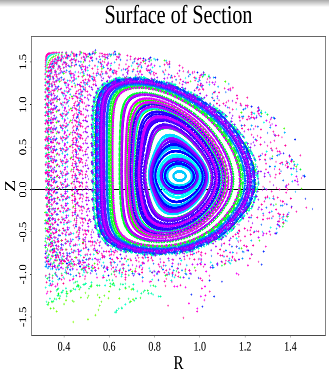
Coherent filaments also form in single X point configuration

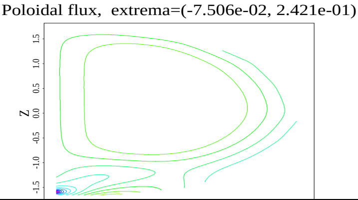
Nonlinear saturated toroidal current density



- Nonaxisymmetric nonlinear mode structure radially extends from the closed flux region to the region of open field lines (outside of separatrix).
- The axisymmetic current density layer is strongly affected by the mode and is broken near the edge region of closed flux surface and is radially expanded in form of coherent filaments.

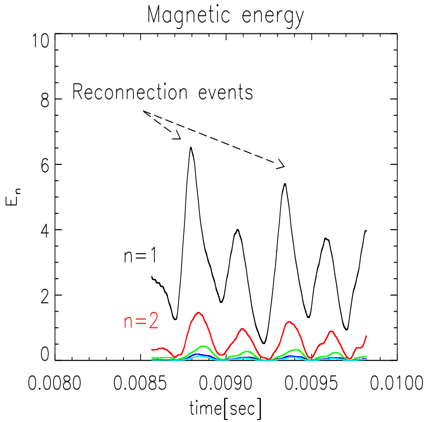
An equilibrium state with closed flux surfaces is fully formed non-inductively





- Puncture plot obtained from the 3-D simulations shows the last closed flux surface (LCFS) extending radially from r= 0.52m-1.26m
- Stochastic region outside of separatrix

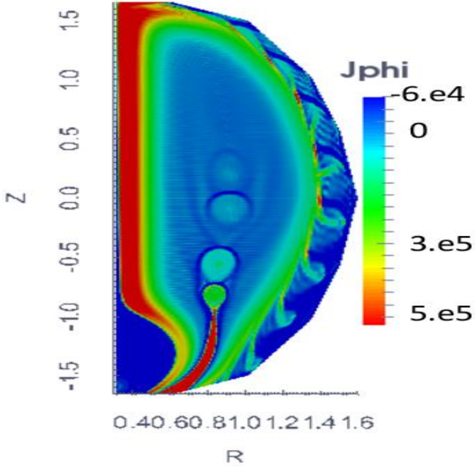
Observed edge localized coherent structures exhibit repetitive cycles during nonlinear stage



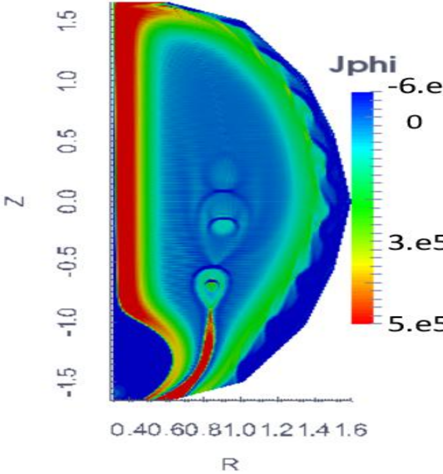
- Energy vs. time during full nonlinear 3-D simulations with 43 toroidal modes and with high toroidal field (B_ϕ =1.23T).
- Nonlinear dynamics during the flat top part of the total current (320kA)

The structures relax back radially to merge back into an axisymmetric toroidal current density

maximum fluctuations



minimum fluctuations



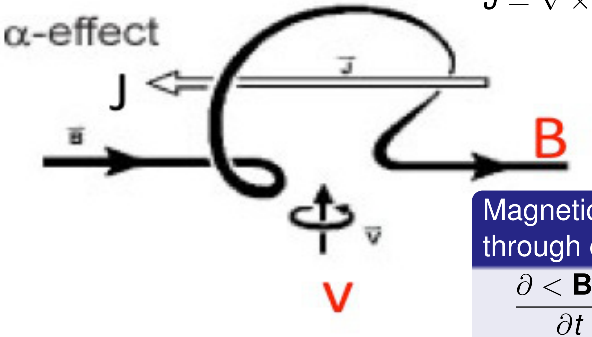
Due to higher toroidal field, only the outer edge (on the low field side) remains strongly perturbed

Both nonaxisymmetric edge current and emf contribute to the quasiperiodic dynamics

consider: $B =< B > + \widetilde{B}$

total

$J = \nabla \times B =< J >_{n=0} + \widetilde{J}_{n\neq 0}$

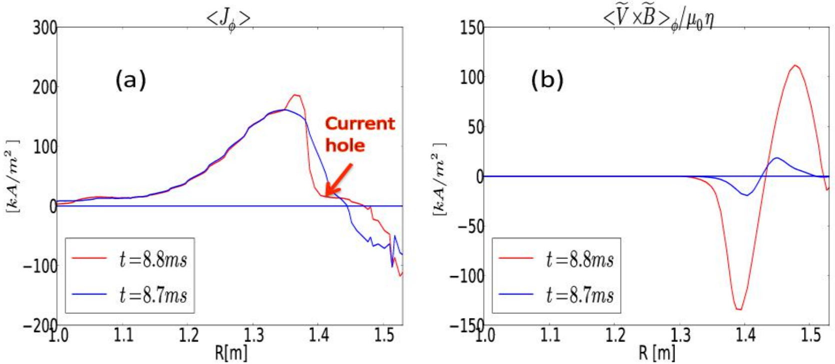


Magnetic field generation through correlated fluctuations

$$\frac{\partial < \mathbf{B} >}{\partial t} = -\nabla \times < \mathbf{E} >$$

$$< \mathbf{E} > = \underbrace{- < \widetilde{V} \times \widetilde{B} >}_{\text{Large-scale}}$$

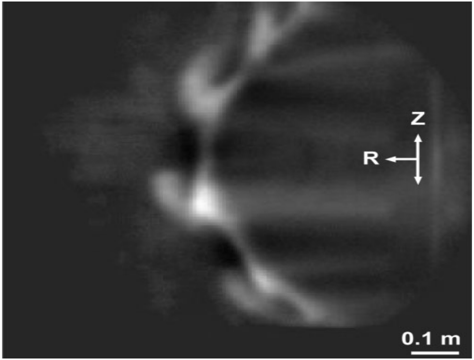
The emf contributes to the formation of current holes and the radially outward expulsion of the current density



The vertically-averaged current density is drastically different because of the nonaxisymmetric fluctuations at t= 8.8ms

The localized dynamo term changes sign around the same radius where the flattening and annihilation of current density occurs

Coherent filament structures found here are very similar to the camera images of peeling modes from Pegasus



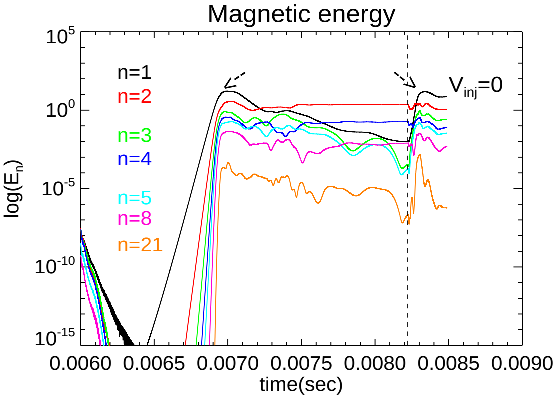
Current-driven peeling modes with $n \leq 3$ were observed. Also low-n ELMs in NSTX [Maingi, et al. PRL 2009]. High m rotating feature during disruption in HBT-EP [Levesque]

- J_{edge} generated by large skin currents during standard confinement
- $J_{||}/B$ peeling drive found during strong rampup of Ohmic discharges
- High poloidal coherence, with the intensity of the filament structures rising and falling in about $50\mu s$ [Bongard, et al. PRL 2011, Thome et al. PRL 2016]

III- The observation of non-axisymmetric edge current density during plasma vertical displacement (VDEs)

- By driving large current in the open field region, the stability of scrape-off layer currents (halo currents) can be studied
- Voltage is turned off to allow vertical displacement downward

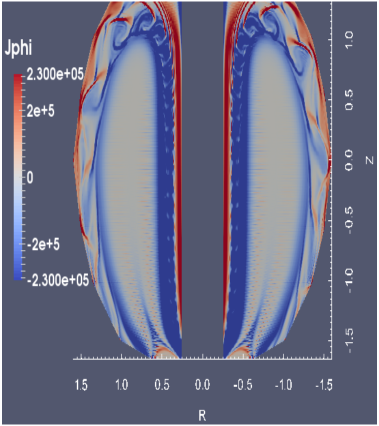
Strong 3-D dynamics as the plasma is being vertically displaced

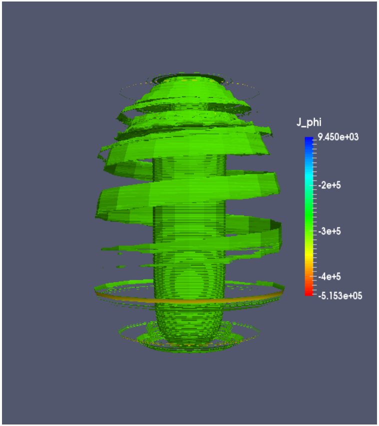


Low-n current-sheet instability triggered when the plasma is vertically expanding upward and when decaying downward
The observation of non-axisymmetric edge current density during plasma vertical displacement (VDEs)

Nonlinear current-carrying filaments are formed during vertical displacement of plasma

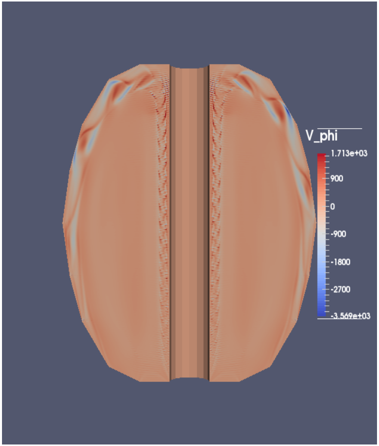
t=6.98 ms

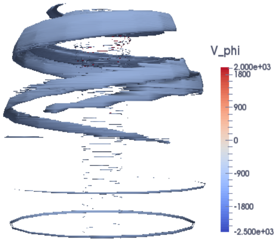




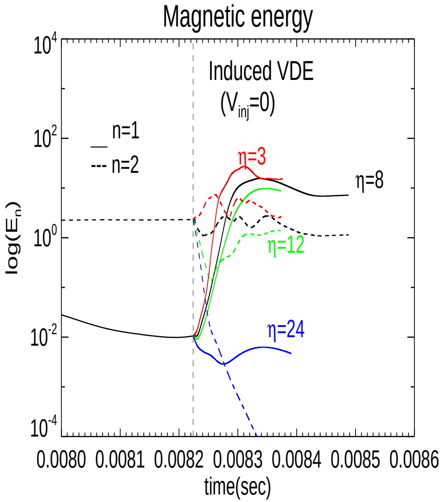
Nonlinear current-carrying filaments do rotate toroidally

Toroidal velocity



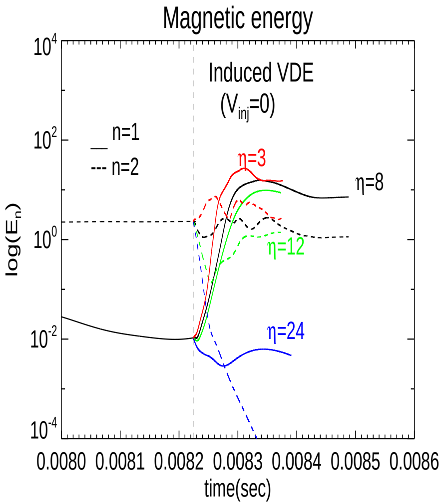


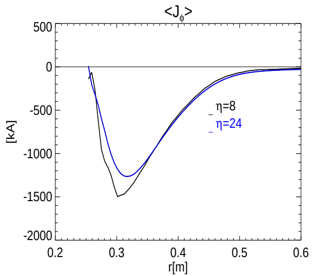
The effect of edge magnetic diffusivity on VDE stability is studied in 3D simulations

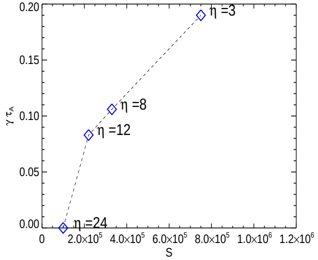


- Several 3-D simulations at different magnetic diffusivities are performed when plasma vertical displacement is induced by turning off the voltage.
- The filaments do saturate grow and saturate at higher amplitudes at lower magnetic diffusivity.

Filaments are stable when the rate of edge current diffusion is fast

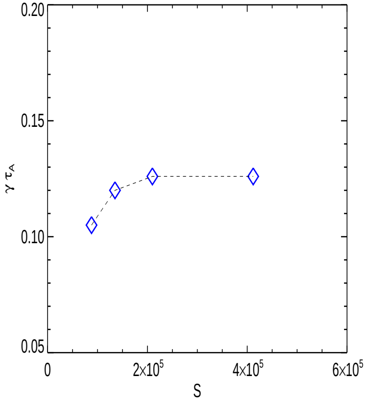


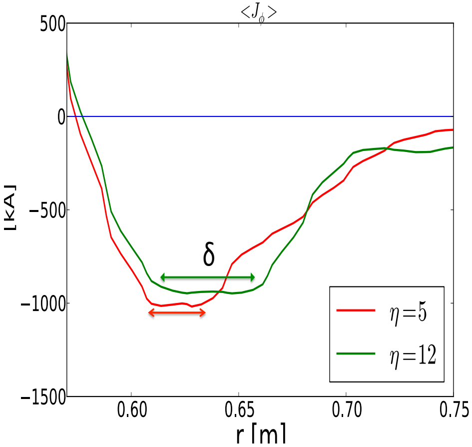




The growth rate of the edge filamentary structures becomes independent of Lundquist number.

As for a fixed maximum current density amplitude, the width of the current layer scales with S, the 3-D instability grow nearly independent of S.





Summary

- A transition to plasmoid instability has for the first time been predicted by simulations in a large-scale toroidal fusion plasma. [Ebrahimi&Raman PRL 2015]
- Motivated by the simulations, experimental camera images exhibit the existence of reconnecting plasmoids in NSTX.
- **For the first time, a 3-D dynamo poloidal flux amplification is observed to trigger axisymmetric reconnecting plasmoids.)** [Ebrahimi PoP Letter 2016]

Our simulations shed light onto the role of reconnection in ELM nonlinear dynamics of a tokamak

- Observation of nonlinearly formed nonaxisymmetric edge current
- The quasiperiodic dynamics of ELMs are explained as reconnection events through a fluctuation-induced bi-directional emf dynamo term. [Ebrahimi PoP 2017]